

# Too small to succeed? Lighting up massive dark matter subhaloes of the Milky Way

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## ABSTRACT

Using Constrained Local UniversE Simulations (CLUES) of the formation of the Local Group in a cosmological context we investigate the recently highlighted problem that the majority of the most massive dark subhaloes of the Milky Way are too dense to host any of its bright satellites. In particular, we examine the influence of baryonic processes and find that they leave a twofold effect on the relation between the peak of the rotation curve and its position ( $V_{\max}$  and  $R_{\max}$ ). Satellites with a large baryon fraction experience adiabatic contraction thus decreasing  $R_{\max}$  while leaving  $V_{\max}$  more or less unchanged. Subhaloes with smaller baryon fractions undergo a decrease in  $V_{\max}$  possibly due to outflows of material. Furthermore, the situation of finding subhaloes in simulations that lie outside the confidence interval for possible hosts of the bright MW dwarf spheroidals, appears to be far more prominent in cosmologies with a high  $\sigma_8$  normalisation and depends on the mass of the host. We conclude that the problem cannot be simply solved by including baryonic processes and hence demands further investigations.

**Key words:** methods: numerical -  $N$ -body simulations – galaxies: formation - haloes - Local Group

## 1 INTRODUCTION

The  $\Lambda$  Cold Dark Matter ( $\Lambda$ CDM) model, first explored more than two decades ago (Davis et al. 1985), has been very successful in explaining a multitude of observations at cosmological scales, such as anisotropies of Cosmic Microwave Background radiation (CMB) Jarosik & et al. (e.g. 2011) and galaxy clustering on large scales (e.g. Cole & et al. 2005). However, on smaller, galactic scales the tests of the  $\Lambda$ CDM model are complicated by the baryonic physics involved in galaxy formation. Therefore, testing the currently accepted concordance model at these scales is necessary in order to not only understand the nature of dark matter but also the accuracy of the model itself.

The validity of the  $\Lambda$ CDM model on galactic scales is still being questioned due to the discrepancy between the number of observed satellites and the number of predicted dark matter subhaloes. High resolution simulations of galactic-size haloes resolve a substantial number of substructures within the virial radius, as

first pointed out by Klypin et al. (1999) and Moore et al. (1999), and recently reviewed by Kravtsov (2010) and Bullock (2010).

The most popular interpretation of this so-called “Missing Satellite Problem” requires that the smallest dark matter haloes are inefficient at forming stars (e.g. Bullock 2010; Kravtsov 2010). Mechanisms such as early reionization of the intergalactic medium and supernovae feedback have been invoked to identify the halo mass scale where the galaxy formation starts to be inefficient (Bullock et al. 2000; Somerville 2002; Benson et al. 2002), partially solving the problem. Furthermore, the detection of satellites is most certainly biased because of current detection limits (Tollerud et al. 2008; Walsh et al. 2009).

There is yet another aspect of the satellite population that needs to be addressed: the mismatch between the predicted and inferred distribution of  $V_{\max}$  values at the high- $V_{\max}$  end as recently highlighted by Boylan-Kolchin et al. (2011), where  $V_{\max}$  measures the peak of the rotation curve of subhaloes. Using the Aquarius simulations (Springel et al. 2008) and the Via Lactea II simulation (Diemand et al. 2008) they found that the majority of the most massive subhaloes (i.e. the high- $V_{\max}$  objects) of the Milky Way are too dense to host any of its bright satellites.

There are a number of ways in which this discrepancy may be resolved: the subhalo mass function of the Milky Way could be

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a statistical anomaly with respect to the  $\Lambda$ CDM expectations (Liu et al. 2010; Guo et al. 2011), or the fundamental assumption that the luminosities of the satellites are not monotonically related to the mass of the subhaloes does not hold true.

In response to the claims by Boylan-Kolchin et al. (2011), Lovell et al. (2011) explored the possibility that warm rather than cold dark matter can provide a better match to the inferred distribution of satellite circular velocities. With a power spectrum suppressed at masses below  $\sim 10^{10} M_\odot$  (corresponding to a warm mass of 2 keV), they found that a warm dark matter model naturally produces haloes that are less concentrated than their cold dark matter counterparts. The attempt to explain the evolution of small scale structures in the local universe with a  $\Lambda$ WDM model was already presented in Tikhonov et al. (2009). However, this is only one possible solution to the problem.

Baryonic processes will most certainly also affect the dark matter distribution. Blumenthal et al. (1986) showed that dissipative baryons will lead directly to the adiabatic contraction of the halo increasing its central density, thus being a critical ingredient to determine subhalo properties. However, the possibility that the influence of baryons will lead to a flattening of the dark matter central density cusp (through dynamical friction of infalling substructures composed of dark matter *and* baryons) has, for instance, been suggested by El-Zant et al. (2001) and further studied in Romano-Díaz et al. (2008). Another way in which the haloes' density can be reduced is through sudden mass outflows that can alter substantially the central structure, as suggested by Navarro et al. (1996). In a recent work of Parry et al. (2011) this last scenario has been tested by following the evolution of one simulated satellite, with promising results. The same authors though also showed that the inclusion of baryons in simulations does not seem to have any correlation with the increase or decrease of the dark matter central density.

In this *Letter* we directly address the issue of the  $V_{\max}$  problem in  $\Lambda$ CDM simulations by comparing two identical simulations with each other: one that is solely based upon dark matter physics and another incorporating all the relevant baryonic physics. These simulations form part of the CLUES project<sup>1</sup>, in which the initial conditions are set by imposing constraints derived from observational data of the Local Group. The main feature of using constrained simulations is that it provides a numerical environment that closely matches our actual neighborhood.

## 2 THE SIMULATIONS

### 2.1 Constrained Simulations of the Local Group

We use the same simulations already presented in Libeskind et al. (2010), Libeskind et al. (2011), Knebe et al. (2010), and Knebe et al. (2011) and refer the reader to these papers for a more exhaustive discussion and presentation of these constrained simulations of the Local Group that form part of the CLUES project. However, we briefly summarize their main properties here for clarity.

We choose to run our simulations using standard  $\Lambda$ CDM initial conditions, that assume a WMAP3 cosmology (Spergel et al. 2007), i.e.  $\Omega_m = 0.24$ ,  $\Omega_b = 0.042$ ,  $\Omega_\Lambda = 0.76$ . We use a normalization of  $\sigma_8 = 0.75$  and a slope of the power spectrum of  $n = 0.95$ . We used the treePM-SPH MPI code GADGET2 (Springel 2005) to simulate the evolution of a cosmological box with side length of  $L_{\text{box}} = 64h^{-1}\text{Mpc}$ . Within this box we identified (in

a lower-resolution run utilizing  $1024^3$  particles) the position of a model local group that closely resembles the real Local Group (cf. Libeskind et al. 2010). This Local Group has then been re-sampled with 64 times higher mass resolution in a region of  $2h^{-1}\text{Mpc}$  about its centre giving a nominal resolution equivalent to  $4096^3$  particles giving a mass resolution of  $m_{\text{DM}} = 2.1 \times 10^5 h^{-1} M_\odot$  for the dark matter and  $m_{\text{gas}} = 4.42 \times 10^4 h^{-1} M_\odot$  for the gas particles. For more details we refer to the reader to Gottlöber et al. (2010).

For this particular study we further use a gas dynamical SPH simulation started with the same initial conditions, in which we additionally follow the feedback and star formation rules of Springel & Hernquist (2003): the interstellar medium (ISM) is modeled as a two phase medium composed of hot ambient gas and cold gas clouds in pressure equilibrium. The thermodynamic properties of the gas are computed in the presence of a uniform but evolving ultra-violet cosmic background generated from QSOs and AGNs and switched on at  $z = 6$  (Haardt & Madau 1996). Cooling rates are calculated from a mixture of a primordial plasma composition. No metal dependent cooling is assumed. Cold gas cloud formation by thermal instability, star formation, the evaporation of gas clouds, and the heating of ambient gas by supernova driven winds are assumed to all occur simultaneously. Note that the results presented through the paper will only refer to the specific SF/feedback model of Springel & Hernquist (2003): other formalisms might lead to different conclusions, and will be addressed in a companion paper (Di Cintio et al., in preparation).

In addition we also have at our disposal a dark matter only CLUES simulation based upon the WMAP5 cosmology (Komatsu et al. 2009) whose details will be presented in a companion paper; here it suffices to know that this simulation has the same formal resolution as the WMAP3 one, and it has also been re-simulated within a sphere of  $2h^{-1}\text{Mpc}$  radius, i.e. the primary difference between the two simulations is merely the cosmology.

### 2.2 The (Sub-)Halo Finding

We used the MPI+OpenMP hybrid halo finder AHF (AMIGA halo finder) to identify haloes and subhaloes in our simulation<sup>2</sup>. AHF is the successor of the MHF halo finder by Gill et al. (2004), and a detailed description of its mode of operation is given in the code paper (Knollmann & Knebe 2009). Note that AHF automatically (and essentially parameter-free) finds haloes, sub-haloes, sub-subhaloes, etc. As the two WMAP3 simulations started with the same initial conditions (apart from the baryons) we can match individual subhaloes in the DM only simulation with a “sister” subhalo in the SPH run (see Libeskind et al. 2010). In effect, this cross identification pairs subclumps at  $z = 0$  that originated from the same overdensity in the initial conditions.

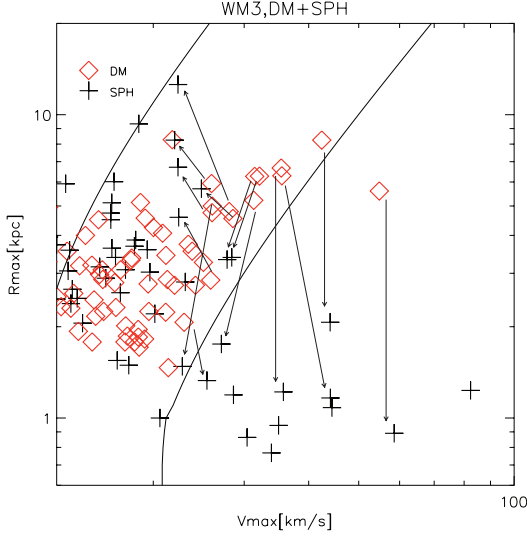
## 3 RESULTS

In order to most closely match the results presented by Boylan-Kolchin et al. (2011) and not to be contaminated by numerical effects we limited the subhaloes used throughout the study to those within 300kpc from their respective host and more massive than  $M_{\text{sub}} > 2 \cdot 10^8 M_\odot h^{-1}$ . We further stack the data for the two most massive hosts representing our MW and M31 galaxies.

In Fig. 1 we show the relation between  $R_{\max}$  and  $V_{\max}$  for

<sup>1</sup> <http://www.clues-project.org>

<sup>2</sup> AHF is freely available from <http://popia.ft.uam.es/AMIGA>

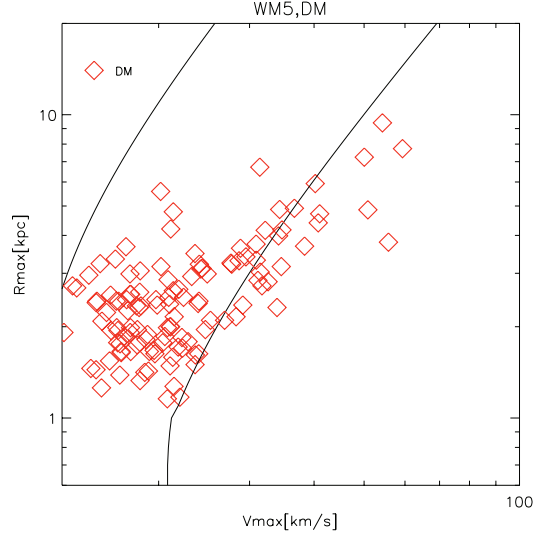


**Figure 1.** The relation between the peak of the rotation curve  $V_{\max}$  and its position  $R_{\max}$  for the WMAP3 simulations: the diamonds are DM only subhaloes, the cross represent baryonic SPH subhaloes. The two solid lines delimit the  $1\sigma$  confidence interval of the observed bright Milky Way dwarf spheroidal galaxies, as in Boylan-Kolchin et al. (2011). The arrows connect the DM-SPH sister pairs found following the matching haloes procedure of Libeskind et al. (2010).

the WMAP3 simulation alongside the  $1\sigma$  confidence region of the known Milky Way satellites, assuming that the mass density profile of the subhaloes containing the nine observed dwarf spheroidal follows a NFW profile (Navarro et al. 1996): the two solid lines in Fig. 1 (and 2) thus limit the area consistent with the observed half-light radii and masses of these dwarfs, based on the work of Wolf et al. (2010). The diamonds represent the subhaloes in the dark matter only simulation while the crosses are the satellite galaxies in the SPH run. The lines connect the sister haloes, i.e. those objects that could be cross-identified in the two simulations. Please note that not all subhaloes could be cross-identified and hence only a certain number of them are connected by arrows. The results for the WMAP5 (dark matter only) data are presented separately in Fig. 2.

The results of these plots are quite interesting. First of all we notice that massive subhaloes (i.e. high- $V_{\max}$  objects) appear to be outside the observational range only in the case of the WMAP5 cosmology. This is thus in agreement with the findings of Boylan-Kolchin et al. (2011) whose Fig.2 shows both the Aquarius and Via Lactea II simulation data combined. The latter run used a  $\sigma_8 = 0.74$  which is close to our WMAP3 value. Note that for this simulation the subhaloes are found only marginally outside the observational confidence interval. However, note that the actual  $V_{\max}$  values for the subhaloes depend on the host mass and  $V_{\max, \text{host}}$ , respectively (cf. Reed et al. 2005; Diemand et al. 2007; Springel et al. 2008). Therefore, in order to better compare the WMAP5 to the WMAP3 simulation, we scaled the subhaloes' maximum velocities,  $V_{\max, \text{sub}}^{WM5}$ , by the ratio  $V_{\max, \text{host}}^{WM3}/V_{\max, \text{host}}^{WM5}$  (not presented here) where the respective values are  $V_{\max, \text{MW}} = 131$ ,  $V_{\max, \text{M31}} = 128$  for WMAP3, and  $V_{\max, \text{MW}} = 178$ ,  $V_{\max, \text{M31}} = 194$  for WMAP5 (all in km/s). We find that this re-normalization leads to a  $\approx 30\%$  decrease of the  $V_{\max, \text{sub}}^{WM5}$  values, bringing them into agreement with the WMAP3 results. In that respect, the two dark matter only simulations are in fact not too different!

More importantly, we see in Fig. 1 that the inclusion of bary-



**Figure 2.** The same as Fig. 1 but for the WMAP5 (dark matter only) simulation.

onic physics does not solve the problem of the massive and highly concentrated dark matter subhaloes. On the contrary subhaloes with baryons appear to be down-shifted in the  $R_{\max}$ - $V_{\max}$  plane with respect to their dark matter counterpart, sometimes even entering the regime outside the observational constraints only in the SPH run. However, we also find that the lower- $V_{\max}$  objects seem to be shifted in the direction anticipated by Boylan-Kolchin et al. (2011), i.e. to the upper left of the plot. There appear to be two competing effects moving subhaloes in the  $R_{\max}$ - $V_{\max}$  plane.

The six SPH (sister) subhaloes that are outside the confidence range have a smaller  $R_{\max}$  than their DM only companion: the addition of baryons causes a contraction of the halo. This effect is also visible for three SPH (sister) subhalo inside the observational area and is readily explained by the physical phenomenon of adiabatic contraction (Blumenthal et al. 1986; Gnedin et al. 2004). We confirm that the baryon fraction  $f_b = \Omega_b/\Omega_m$  of those subhaloes moving downwards is higher than for the subhaloes shifted to the upper left. On average, the baryon fraction of the nine (sister) SPH subhaloes, whose  $R_{\max}$  is reduced with respect to their DM counterpart, is  $f_b/f_{b, \text{cosmic}} \sim 0.314$ , while the mean  $f_b$  of the SPH subhaloes inside the  $1\sigma$  area whose  $R_{\max}$  increases is  $f_b/f_{b, \text{cosmic}} \sim 0.006$ , i.e. substantially smaller. The subhaloes with high  $f_b$  experience adiabatic contraction and the majority of these objects are the ones with the initial highest  $R_{\max} - V_{\max}$  pairs.

To confirm this last point, we used the CONTRA code (Gnedin et al. 2004) to calculate the adiabatic contraction of a dark matter halo in response to condensation of baryons. Using our numerical data as input parameters, we found that adiabatic contraction is actually efficient only for those subhaloes with sufficiently high  $f_b$ , as expected: the amount of the  $R_{\max}$  reduction computed this way perfectly matches the observed shifts in Fig. 1.

Instead, for the lower  $V_{\max}$  sister subhaloes (with substantially smaller baryon fractions) the baryonic matter has the capability to lower the maximum velocity of the rotation curves, while increasing  $R_{\max}$ . This has already been claimed in previous works and may be due to different mechanisms. In particular, we like to highlight the mass outflow model of Navarro et al. (1996): immediate expulsion of a large fraction of baryonic material during star

formation could be the cause of the creation of a central dark matter core, which will move the peak of the rotation curve to larger radii. This model has been successfully tested by Parry et al. (2011) who followed the formation history of a single stellar dominated satellite, which undergoes the sequence of events predicted by Navarro et al. (1996). Another possible explanation to end up with less concentrated density profiles, is through the mechanism described by Mashchenko et al. (2006). A random bulk motion of gas, driven by stellar feedback, results in a flattening of the central DM cusps, thus leading to DM densities smaller than predicted by pure DM cosmological models. But why is it that those objects with low baryon fractions are the ones that require the aforementioned mechanisms? Is it that the gas expulsion has already occurred, thereby lowering the baryon fraction? Possibly the baryon fraction is only low at redshift  $z = 0$  because of mass losses during the subhaloes history? Lately, Nickerson et al. (2011) explored the effect of several baryon loss mechanisms on subhaloes in SPH simulation of a Milky Way like galaxy, too: they found that for the subhaloes which ended up having (or having had) stars but no gas the most efficient mechanism of baryons removal is exactly the stellar feedback (Dekel & Silk 1986). Finally, we note that the adiabatic contraction (following Gnedin et al. (2004)) is ineffective for these subhaloes. We will address all these issue of the temporal evolution, mass loss and baryon influence in greater detail in a companion paper (Di Cintio et al., in preparation).

We close this Section with a detailed look at the rotation curves of the sister haloes in Fig. 3. In each plot the two sister objects are presented; the solid and dashed lines represent the circular velocity of the DM subhaloes in the dark matter only simulation and of the (sister) SPH subhalo, respectively. The asterisks show the  $V_{\max}$ - $R_{\max}$  pairs used in Fig. 1. We thus observe adiabatic contraction at work: the first three objects (which happen to have high baryon fraction) in that plot clearly show the centrally peaked total matter distribution in the SPH run. The plot further indicates that our measurements of the rotation curve and its peak are not contaminated by numerical artifacts (e.g. mis-identified halo centre, etc.).

## 4 CONCLUSIONS

In this letter we explored the possibility that baryonic processes may solve the recently presented problem of "the puzzling darkness of Milky Way subhaloes" (Boylan-Kolchin et al. 2011). To this extent, we used dark matter only as well as full hydrodynamical simulations of cosmic structure in the context of the CLUES project. We used cosmological parameters determined from both the WMAP3 and WMAP5 data.

Our conclusions are twofold and can be summarized as follows:

- We find that when baryonic physics is included, following the feedback and star formation prescriptions of Springel & Hernquist (2003), the problem of having too dense massive subhaloes is not solved. Instead, gasdynamical simulations pose new questions regarding which mechanisms are responsible for the lowering of  $R_{\max}$  in those subhaloes (while  $V_{\max}$  remains more or less constant). Adiabatic contraction seems to be a reasonable explanation, as shown using the modified adiabatic contraction model of Gnedin et al. (2004): this process is effective only for some subhaloes, specifically, for those with a high baryon fraction. For the SPH subhaloes with lower baryon fractions at redshift  $z = 0$ , instead, we observe a general increase of  $R_{\max}$  with respect to their

DM counterpart, thus meaning that other effects are at work, e.g. the model proposed by Navarro et al. (1996) in which a rapid expulsion of baryonic mass during star formation causes a reduction of the halo concentration, as well as naturally explaining the low baryon fraction of these objects.

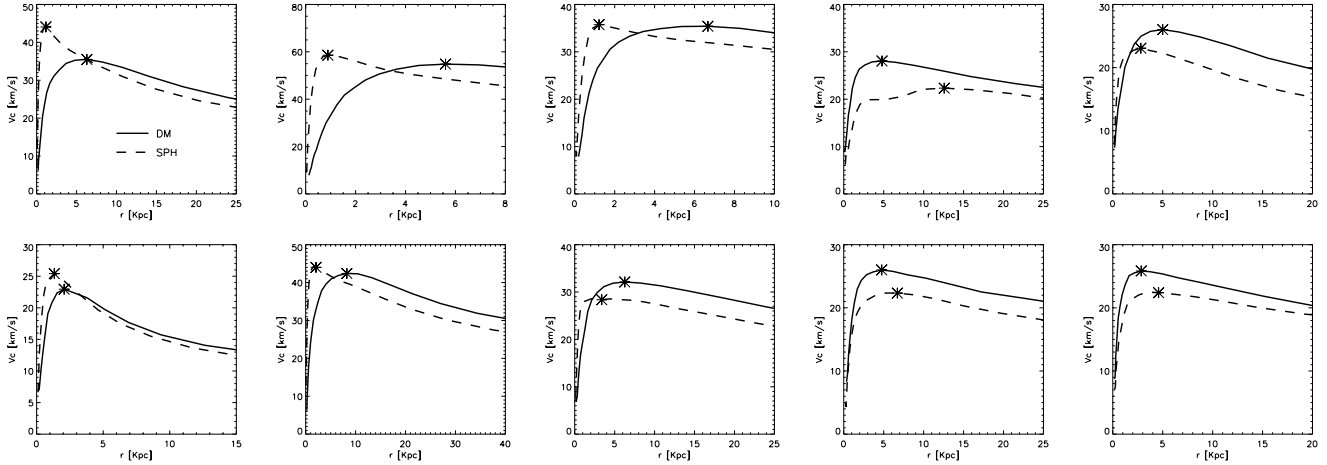
- While in the WMAP5 DM only case we find dark matter subhaloes outside the confidence area (calculated following the prescription given in Boylan-Kolchin et al. (2011)) in the WMAP3 cosmology we only have one massive subhalo outside this observational range. Since the Via Lactea II and Aquarius simulations presented in Boylan-Kolchin et al. (2011) are similar cases, we conclude that the cosmology certainly has an influence, too: the higher  $\sigma_8$  of the WMAP5 scenario eventually led to higher host masses which – according to our test – are the most likely reason for the higher number of excessively centrally concentrated substructures. Note that the latest data from WMAP7 favours  $\sigma_8 = 0.807$ , a value between the WMAP3 and WMAP5 results: this could mean that the problem is worse than in WMAP3, but not as pronounced as in the WMAP5 case.

An issue neither touched upon by us nor other authors is the adequacy of using NFW profiles when calculating the confidence interval for possible hosts of the bright MW dwarf spheroidals. It is obvious that tidal effects will lead to severe modifications of the original NFW density profile subhaloes had upon infall into their host (Kazantzidis et al. 2004). They therefore leave an impact upon internal and kinematical properties, respectively (Lokas et al. 2010, 2011), which should be taken into account when using observed half-light radii  $R_{1/2}$  and their corresponding masses  $M_{1/2}$  to define the confidence interval. Further, Romano-Díaz et al. (2008) showed that adiabatic contraction makes the dark matter profile almost isothermal. However, the relevance is questionable as material will primarily be stripped from the outer regions: Peñarrubia et al. (2008) state that dSphs embedded in NFW haloes are very resilient to tidal effects until they are nearly destroyed. This is supported by Navarro et al. (2010) who found that the NFW shape holds reasonably well even for subhaloes. To roughly gauge the problem, we fitted our (SPH) subhaloes to a NFW profile, and observed that while some of them are well fitted, there are still objects whose density profile cannot be approximated by the simple NFW functional form. Taking all these considerations into account suggests that the NFW profile used to calculate the allowed region is likely not the best choice.

The interpretation of the results presented here clearly demands a closer investigation of the evolutionary tracks of the satellites, the actual influence of the SF and feedback model as well as an improved calculation of the observational confidence level, verifying the applicability of the NFW approach. However, we leave this to a companion paper (Di Cintio et al., in preparation) and only highlight here that simply the inclusion of baryonic physics does not solve the problem; it rather poses new challenges to be explored and studied in greater detail.

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**Figure 3.** Rotation curves of ten sister pairs of massive subhaloes. In each panel the velocity profile of a pair of DM and SPH subhaloes is presented. The actual values of  $V_{\max} \cdot R_{\max}$  are plotted as asterisks.

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